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Ephemeral gully erosion by preferential flow through a discontinuous soil-pipe

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Abstract

Subsurface flow through soil-pipes can contribute to ephemeral gully erosion but these soil-pipes are cut-off when tillage fills in the gully. The objective was to determine the effect of flow through discontinuous soil-pipes on ephemeral gully erosion. Experiments were conducted on 150 cm long by 100 cm wide soil beds with an artificial soil-pipe at the upper end that extended 50 cm into the soil immediately above a water-restricting horizon. The combination of rainfall with pipe flow produced extensive (63 kg) soil losses by mass wasting. The mode of mass wasting appeared to be sudden, cataclysmic pop-out failures. Total soil loss by sheet erosion with rainfall and pipe flow combined (13.6 kg) was four times higher than by rainfall alone (3.4 kg). Under rainfall with pipe flow, soil loss by mass wasting was nearly 20 times higher than sheet erosion from rainfall alone. Soil conservation practices that treat surface runoff process alone may be ineffective if subsurface flow is contributing.
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Keywords: Ephemeral gully; Erosion; Mass wasting; Preferential flow; Soil-pipes

1. Introduction

Soil erosion by water remains a major problem in many regions of the US. More streams in the US are listed as impaired by sediment than by any other contaminant (United States Environmental Protection Agency, 2000). Nutrients, heavy metals and pesticides are transported with sediment. Predicting and controlling the movement of sediment in a watershed requires a thorough knowledge and understanding of the runoff, erosion, and sediment transport processes. While substantial efforts have been made to describe and control sheet erosion, there is an incomplete understanding of the basic mechanisms governing ephemeral gully erosion, i.e. small channels that can be filled-in by normal tillage.

Estimates by the USDA-Natural Resource Conservation Service (1997) for 17 States suggest that ephemeral gully erosion ranges from 18 to 73% of the total erosion with a median of 35%. Poesen et al. (2003) found that ephemeral gully erosion contributed from 10 to 94% of total field soil loss, with a median estimate of 44%. The role of subsurface flow and soil–water pressures has been shown to be important to rill initiation and growth (Römkens et al., 1997) and numerous papers by geomorphologist have demonstrated its importance to formation of gullies and streambank failure (Faulkner, 2006). The contribution of subsurface flow to ephemeral gully erosion is less well known. The two mechanisms of subsurface flow attributed to gully erosion are seepage flow and preferential flow through soil-pipes (Dunne, 1990). Bryan and Jones (1997) pointed out that many times the term piping is used, as Dunne (1990) did, to refer collectively to both mechanisms of subsurface flow erosion. However, the processes can be distinguished by referring to pipe-erosion as strictly erosion resulting from flow through a discrete macropore or soil-pipe.

Seepage is common where restriction of downward percolation results in lateral flow that emerges from the soil surface.

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Seepage erosion occurs when the seepage rate produces sufficient drag forces to entrain soil particles in which case liquefaction results in erosion. This was the process, also termed sapping, described by Wilson et al. (2007) that resulted in undercutting of streambanks and subsequently to streambank failure. Seepage erosion also contributes to edge-of-field gullies and ephemeral gullies. In contrast, pipe-erosion occurs when rapid and often turbulent preferential flow through soil-pipes erodes the periphery of the macropores due to the shear forces exceeding the frictional strength binding soil particles. Pipe-erosion, also termed tunnel scour, can cause ephemeral gully development when soil-pipes collapse (Faulkner, 2006). Preferential flow through soil-pipes has been attributed to about 60% of the cases of gully erosion under agronomic conditions in European fields (Bocco, 1991).

A common feature for pipe-erosion is the existence of water-restrictive layers (Botschek et al., 2002), which Faulkner (2006) termed duplex soils, that focus flow through soil-pipes; such as observed in loess where ephemeral gullies are eroded down to the fragipan layer and soil-pipes are evident at the gully head immediately above the restrictive layer (Zhu et al., 2002; Wilson et al., 2006). Faulkner (2006) noted that pipe-erosion may be occurring with no visible evidence until pipe collapse results in an ephemeral gully at an advanced stage of development. Farifteh and Soeters (1999) identified, by aerial photos and verified by ground-truthing, over 900 gullies in a 12 km^2 area of southern Italy developed by pipe collapse and postulated that the real number was substantially higher. The most consistent factors attributed to gullies formed from pipe-erosion are: (i) soil with a permeability contrast (duplex soils) in which soil-pipes tend to form immediately over the water-restricting layer, (ii) sufficient slope to produce hydraulic gradients to drive the preferential flow, and (iii) dispersive soils that are prone to pipe collapse.

Quantification of these factors is seriously lacking. Ephemeral gullies are particularly unique in that, by definition, tillage operations fill-in the gully. Soil-pipes below the depth of tillage will remain intact within the tilled field. However, the soil-pipe, which was previously at the gully head, will be buried and discontinuous. The role of discontinuous soil-pipes on re-establishment of ephemeral gullies has not been quantified. This work also applies to soil-pipes within the depth of tillage that are cut-off, i.e. discontinuous, where they enter the tilled field. The objective of this study was to quantify the hydrologic conditions under which preferential flow through discontinuous soil-pipes initiate ephemeral gullies.

2. Materials and methods

Rainfall simulations were conducted on soil beds in a rectangular flume (Fig. 1) at 5% slope with and without subsurface flow through an artificial soil-pipe. Bulk topsoil was collected from a depth of 0 to 10 cm from a Providence silt loam (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) soil on the Holly Springs Experiment Station (HSES) of the Mississippi Agricultural and Forestry Experiment Station. The topsoil contains 15, 69, and 16% sand, silt, and clay respectively, with 23% stable aggregates (Kemper and Rosenau, 1986), 0.9% organic matter, pH of 6.4, and a C/N ratio of 8.3. Soil was sieved to <2 mm and maintained in field-moist conditions (gravimetric water content of 19%) until packing. Soil of known mass was packed in 2.5 cm lifts using field-moist soil after accounting for the measured water content. The bottom 5 cm of the soil bed mimicked a water-restrictive layer by packing silty clay loam material to the average bulk density (1.57 g cm^{-3}) of fragipans in this area (Rhoton and Tyler, 1990). The topsoil was packed to a bulk density of 1.35 g cm^{-3} above the restrictive layer to form a 30 cm silt loam layer.

Tensiometers were inserted vertically into the soil bed (Fig. 1) such that the ceramic cup was positioned 1 cm above the water-restrictive layer. Twelve tensiometers were installed in a four row by three column array and monitored on 1 min cycles by a datalogger. The four rows were spaced 30 cm apart starting 5 cm from the end of the soil-pipe, i.e. at distances of 95, 65, 35, and 5 cm from the open face. The middle column was positioned at the center of the soil bed, with a column on each side spaced 20 cm from the middle column at distances of 30, 50, and 70 cm from the side of the soil bed.

The flume (Fig. 1) was 150 cm long by 100 cm wide by 50 cm high and constructed from 2 cm thick plexiglass. The endplate at the lower end was removed after packing the soil bed such that gully development would not be hindered by the endplate during flow events. The upper end had a port for connecting an artificial soil-pipe, immediately above the water-restrictive layer, to a water reservoir. The hydraulic head on the soil-pipe was controlled by a Mariotte device. The soil-pipe was a 2 cm i.d. soaker hose that extended 50 cm from the upper end into the soil bed with the end of the pipe left open. Thus, the soil-pipe was at a depth of 28–30 cm which is below the depth of tillage.

Subsurface flow through the soil-pipe was simulated under a constant pressure head of 15 or 30 cm. Pieziometric observations on loess soils with a fragipan have indicated that perched water tables often reach the soil surface during winter storm events. The hydraulic head established is therefore governed by the depth to the fragipan horizon. Fragipan depths are highly variable due to past erosion but typically range from 15 to 112 cm at the HSES (Rhoton and Tyler, 1990) which is typical of the loess region. Therefore, the simulated hydraulic heads on the artificial pipe are reasonable.

The rainfall simulator (Meyer, 1960) consisted of a series of oscillating Veejet nozzles (80100) located approximately 3 m above the soil surface. Nozzles traversed the area horizontally in two dimensions in order to apply a uniform rainfall application with an impact energy of 211 kJ ha^{-1} mm^{-1}. Rainfall was applied at a rate of 65 mm h^{-1} for 1 h under antecedent soil–water conditions (dry run), followed 0.5 h later by a 0.5 h duration rainfall (wet run), and a final 0.5 h duration rainfall (very wet run) 0.5 h after the wet run. Ground water from wells on the HSES was used for soil-pipe and rainfall applications to mimic soil–water ionic strengths.

The following combinations of experiments were conducted in replicate runs: (1) pipe flow only with 15 cm pressure head, (2) pipe flow only with 30 cm pressure head, (3) rainfall only, (4) rainfall and pipe flow with a 15 cm head, and (5) rainfall and pipe flow with a 30 cm head. The time of runoff and/or seepage flow initiation was recorded and the runoff rate measured by collecting runoff for 15 s every 3 min until rainfall was terminated, at which

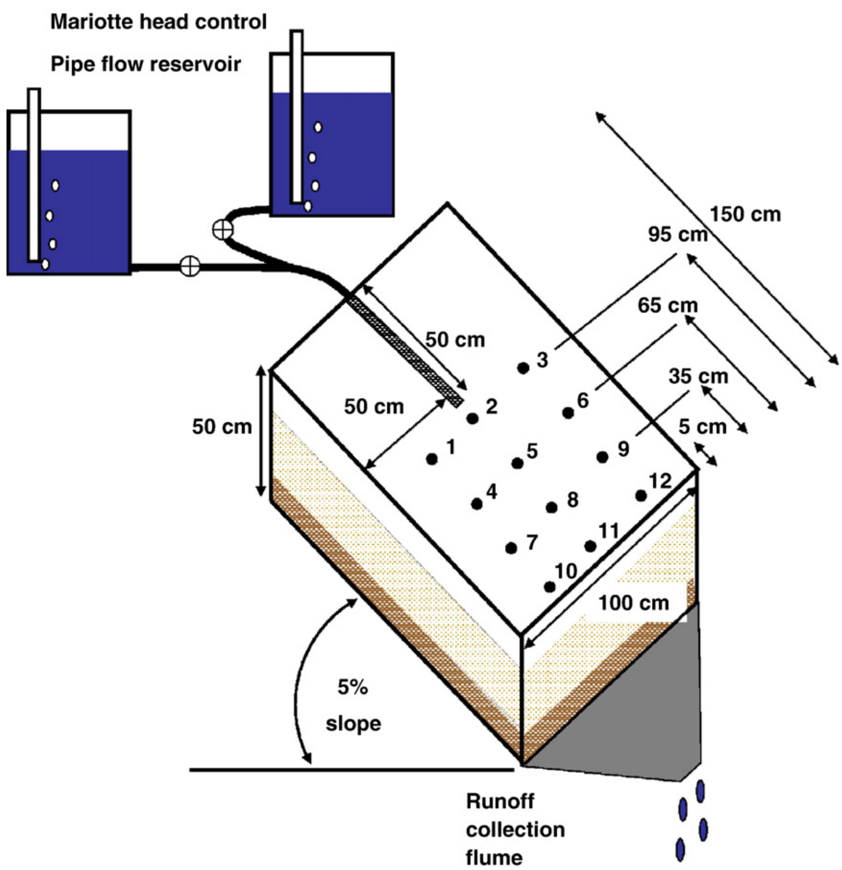

Fig. 1. Illustration of soil bed in a 100 cm wide by 150 cm long by 50 cm high flume at a 5% slope with a 50 cm long porous soil-pipe at the upper end and an open face lower end. Tensiometer locations are indicated by solid circles with their numbering scheme indicated. The water reservoir for the soil-pipe has a Mariotte device for head control.

point runoff was collected for 15 s every minute until runoff ceased. Runoff volume was recorded and sediment content analyzed by decanting excess water and then evaporating to oven-dryness (105 °C). The timing and soil loss by mass wasting were recorded. Slumped material was collected manually by cleaning out the weir section of the lysimeter immediately after mass failure. Care was taken to only remove the material in the weir section from the mass wasting while leaving soil deposited from sheet erosion that was not yet sampled. At the point of failure, there would already be material deposited on the weir section from sheet erosion that would be buried by the slumped material. Collecting the slumped material inevitably included some of the material deposited by sheet erosion, however, this was off-set by the inability to collect all the slumped material which would eventually get sampled as sheet erosion. The collapsed material was weighed, and sampled to determine water content. The dry mass of sediment loss by mass wasting was calculated after correcting for the water content.

3. Results and discussion

3.1. Pipe flow impact

Tensiometer values, (Fig. 2A) prior to establishment of the 15 cm head in the soil-pipe, exhibited an average matric head of −27 cm near the end of the soil-pipe (T95) and an average value of −44 cm just 5 cm from the open face (T05). Thus, there was a small lateral gradient in addition to the slope towards the outflow end at the start. The flow rate through the soil-pipe averaged 4.1 L h^{-1} with small variance with time (coefficient of variation, CV = 17%). Tensiometers responded in a systematic fashion with tensiometer 2, 5 cm below the pipe and 95 cm from the outlet, responding first at 5.5 min following release. The lateral spread of the wetting front reached tensiometers 3 and 1 at times of 9.7 and 10.7 min, respectively. Then a downslope response at tensiometers in rows 65 cm, 35, and 5 cm from the outlet at times of 19.7 min, 67.5 min, and 169.5 min, respectively. For each distance downslope the tensiometer in the middle (locations 2, 5, 8, and 11 in Fig. 1) responded first followed by lateral spread to the outer tensiometers. In response, seepage began from the open face immediately above the restrictive layer at time of 186 min following establishment of the pressure head.

It is interesting to note that, seemingly contrary to Richards outflow law which states that positive matric heads are required for flow out of the soil through an open face, all three of the tensiometers 5 cm from the face were still under negative matric heads when seepage began. The last row of tensiometers, 5 cm from the face, had begun to respond, Fig. 2A, but none of the three were near saturation, i.e. 0 cm head, at the time of seepage. The reason is likely due to the tensiometer cups being positioned

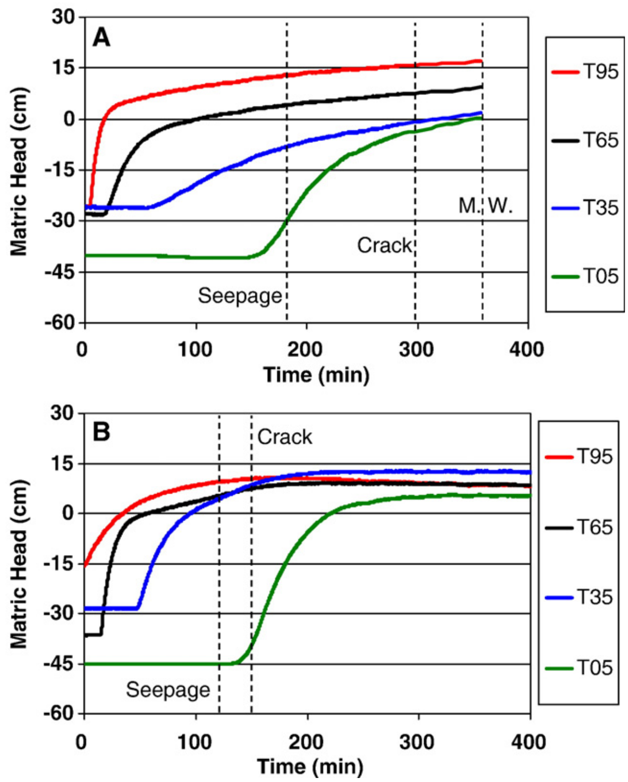

Fig. 2. Tensiometer response to establishment of (A) 15 cm head and (B) 30 cm head on the soil-pipe at positions T2 (95 cm), T5 (65 cm), T8 (35 cm), and T11 (5 cm) in Fig. 1. Vertical dashed lines indicate time to seepage initiation, tension crack development, and mass wasting (MW).

1 cm above the interface of the water-restricting layer. Seepage response clearly indicated hydraulic non-equilibrium conditions caused by preferential flow immediately above the surface of the restrictive layer. The observation of seepage occurring under apparently unsaturated conditions due to preferential flow over a restrictive layer is consistent with findings by Wilson et al. (2007) and Fox et al. (2006) for streambank failure due to seepage erosion.

Seepage continued for an additional 107 min with negligible soil loss at which time a tension crack was observed on the surface on the left side 38 cm from the front face. The crack was concave inward with a maximum distance of 44 cm from the face at 15 cm from the left side then extended diagonally across the soil bed to the open face 20 cm from the right side. The aperture of the crack was negligible when first observed but steadily grew to greater than 1 cm. No flow was observed from the crack where it entered the open face. At 355 min into the pipe flow event, there was a sudden and cataclysmic mass wasting event in which approximately 2.2 kg of soil was lost from the middle of the front face. This was followed by three additional mass wasting events over the next 10 min for a total soil loss of 24.0 kg. The mass wasting occurred by what is commonly termed pop-out failures. The soil stabilized with only about half of the volume of the bed dissected by the crack being lost by mass wasting.

The condition of flow though a discontinuous soil-pipe under 15 cm pressure head was repeated with a drastically different response. In the subsequent test, the tensiometer values averaged −46 cm with negligible lateral gradient. The flow rate through the soil-pipe was 2.5 L h^{-1} which is considerably lower than the 4.1 L h^{-1} observed in the first run and the flow rate decreased dramatically with time down to a mere 0.6 L h^{-1} after 12 h. As a result, seepage and tension cracking were not observed and there was no soil lost by mass wasting.

The condition of pipe flow alone with a 30 cm pressure head was conducted in replicated runs with essentially identical conditions and results. The tensiometer values prior to establishment of the 30 cm pressure head for both runs exhibited a gradient from the soil-pipe at T95 to the open face at T05. The average matric heads of the three tensiometers positioned at the soil-pipe for the two runs were −28 and −35, and averaged −45 and −47 cm for the three tensiometers at the open face, illustrated in Fig. 2B for the center tensiometers during one run. For both runs, as with the 15 cm head, the first response to head establishment on the pipe for all four rows was by the middle tensiometers. The time to response was 1 and 2 min at T95, 21 and 15 min at T65, 107 and 50 min at T35, and 257 and 142 min at T05, which correspond to tensiometers 2, 5, 8, and 11 in Fig. 1.

Despite having identical 30 cm pressure heads established on the soil-pipes, the flow rates were dramatically different in the two runs with an average of 2.8 L h^{-1} and 5.2 L h^{-1} over the entire experiment. The first 30 cm test had a steady flow rate of 5.1 L h^{-1} for the first hour before decreasing suddenly to around 2.0 L h^{-1}. Thus, the seepage responses were different with time to initiation of seepage of 311 min and 132 min, respectively. However, for both tests, seepage began prior to establishment of positive pressures in the last row of tensiometer which was consistent with the initial 15 cm head experiment. Additionally, results were also similar to the first 15 cm head run in that in both cases tension cracks developed within the soil bed. Tension cracks are fractures that develop in soil due to differential subsidence as a result of dynamic changes in the stress–strain properties of soil during a flow event. The location and magnitude of the tension cracks were almost identical in the two 30 cm head tests. In both tests, tension cracks formed along the

Table 1
Hydrometric response to pipe flow and rainfall applications in time to seepage (Sp), time to runoff (Ro), runoff rate, pipe flow (PF) rate, sediment concentration, soil loss (SL) by sheet erosion, and mass wasting (MW)

Treatment	Sp time	Ro time	Runoff rate	PF rate	Sed. conc.	SL	MW
	min	min	cm h^{-1}	cm h^{-1}	g L^{-1}	kg	kg
Rain only	N*	3.4a	4.5a	N	22.5a	3.4a	0.0a
15 cm head	186a**	N	0.04b	0.19a	0.2a	0.0a	12.0ab
30 cm head	221a	N	0.03b	0.27a	0.0a	0.0a	0.0a
15 cm and rain	532a	1.8a	5.21a	0.05a	26.8ab	4.5a	16.2ab
30 cm and rain	658a	9.3a	5.24a	0.19a	85.3b	13.6b	62.9b

*The letter N indicates not applicable; **only the value for first test listed as the second test did not exhibit seepage.
Values within a column separated by letters indicate significant differences.
The rates of runoff, Ro, and pipe flow, PF, and the sediment concentration are averages over the total time and the two tests per treatment. Runoff rate is the rate of water flow out of the soil bed by overland and subsurface flow combined. PF rate is the flow rate into the soil-pipe as measured in the reservoir tanks. MW is the total mass of soil loss by pop-out failures.

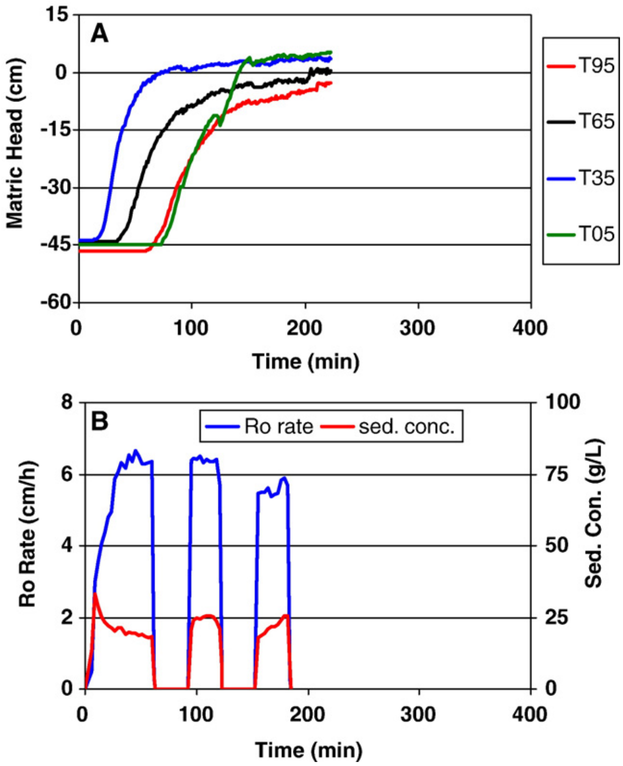

Fig. 3. Data for test 1 of rainfall alone treatment. (A) Tensiometer response to rainfall alone at positions T2 (95 cm), T5 (65 cm), T8 (35 cm), and T11 (5 cm) in Fig. 1. (B) Runoff hydrograph and sedigraph response to the three rainfall events.

front face from the surface down to 5 and 10 cm respectively and were between 20 and 30 cm from the side of the bed. The soil loss was similar to the second run at 15 cm head in that no mass wasting occurred despite the presence of tension cracks.

The results mimicking an ephemeral gully with a soil-pipe that is hydrologically active but has been rendered discontinuous due to the filling-in of the gully is markedly different than observed by Wilson et al. (2006) for a 3 cm diameter soil-pipe at the head of an existing ephemeral gully. They observed soil-pipe flow rates following rainfall events, with rainfall and runoff excluded from the gully, that were typically 1.4 L h^{-1}. This value is lower than the laboratory measurements, however, the laboratory pipe flow rate represents flow through the soil-pipe into the soil bed and not the seepage flow rate out of the bed. The seepage flow rate for the 30 cm head, expressed on a per area basis as a runoff rate in Table 1, from pipe flow alone averaged 0.03 cm h^{-1}, which equates to a flux of 0.5 L h^{-1}. The difference between the pipe flow rate and the seepage rate is due to water storage within the soil bed.

The sediment concentrations observed by Wilson et al. (2006) for their open soil-pipe was between 8.5 and 0.2 g L^{-1} with values typically less than 1 g L^{-1}. In contrast, the sediment concentrations from seepage in the 15 and 30 cm head experiments for a discontinuous soil-pipe were essentially zero. In general, seepage flow rates for pipe flow alone were low, sediment concentrations were negligible and with the exception of one run, the soil bed did not exhibit mass wasting. Therefore soil loss in the runoff from pipe flow alone was negligible. However, soil-pipe flow alone did result in the development of tension cracks. Tension cracks are commonly observed as precursors to bank failure (Fox et al., 2006).

3.2. Rainfall impact

The hydrologic response to rainfall alone, Table 1, was more dynamic than for pipe flow alone. Surface runoff was initiated within 4.5 min and 2.3 min of rainfall for the two tests. The average runoff rate, over the course of the three rainfall events, was 5.3 cm h^{-1} and 3.6 cm h^{-1} for the two tests, respectively. Given the similarity in response, the data from the first test, Fig. 3, are presented to illustrate the rainfall alone behavior. The antecedent conditions were similar to the pipe flow only experiments with matric heads between −43 and −51 cm but with no lateral gradient prior to rainfall. Unlike the pipe flow experiment where tensiometric response sequentially tracked the arrival of a lateral wetting front from the upper to lower position, tensiometric response for rainfall alone indicated random arrival of the vertical wetting front. The middle two rows of tensiometers were the first to respond, ranging from 24 to 37 min, and the last to respond was the most upslope (36 to 106 min) and downslope (56 to 188 min) rows, Fig. 3A. Perched water above the restrictive layer did occur but not in an upslope to downslope chronology as seen for soil-pipe flow. The middle of the soil bed perched water first, at 57 min following rainfall initiation. This occurred 35 cm from the face at tensiometer 7 and spread radially to tensiometers 8 and 9 (also

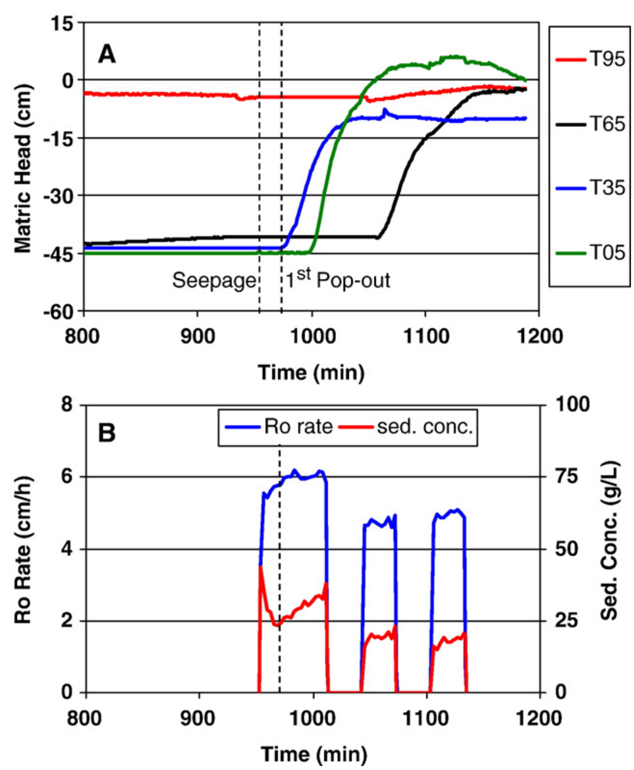

Fig. 4. (A) Tensiometer response to establishment of 15 cm head on the soil-pipe at positions T2 (95 cm), T5 (65 cm), T8 (35 cm), and T11 (5 cm) in Fig. 1. Dashed lines indicate time to initiation of seepage and time of first pop-out failure. (B) Runoff hydrograph and sedigraph response to the three rainfall events for the rainfall plus pipe flow with 15 cm head.

35 cm from the face), followed in order by tensiometers 10 and 11 (both 5 cm from the face), 5 and lastly 6 both 65 cm from the face), Fig. 1. Tensiometers 95 cm from the face never exhibited perched water conditions and interestingly neither did tensiometer 12 just 5 cm from the face.

The sediment concentrations in the surface runoff were fairly dynamic (Fig. 3B) during the first rainfall event, with a peak concentration of 33 g L^{-1} at the initiation of runoff and decreasing to around 18 g L^{-1} as runoff continued with an average of 20.2 g L^{-1}. The second event had stable sediment concentrations around 25 g L^{-1}, while the concentration peaked during the third event at 25.6 g L^{-1} but averaged the same as the first event. The average sediment concentration over the three events for the first test was 21.1 g L^{-1}, which is close to the average of 23.8 g L^{-1} for the second test. The total soil loss by sheet erosion was 3.6 kg and 3.2 kg for the two tests. The average sheet erosion for rainfall alone, under bare soil conditions and a 5% slope, equated to 25 ton ha^{-1} for this single event. This is 3.6 times larger than the tolerable soil loss limit established for this soil for an annual soil loss. Similar to pipe flow, rainfall alone failed to produce mass wasting of the soil bed.

3.3. Synergistic effect of pipe flow with rainfall

The synergistic effect of pipe flow with rainfall was simulated for a 15 cm pressure head and for a 30 cm head with duplicate tests for each treatment. The prescribed hydraulic head was maintained on the pipe until seepage from the soil bed was established then the three sequential rainfall events were initiated.

The two rainfall tests with a 15 cm head had similar responses but with contrasting timing due to differences in antecedent conditions. The initial test was made under much wetter conditions, with tensiometers values averaging −8 cm at the start as compared to an average of −44 cm for the second run, Fig. 4A. As a result, the initial test at the 15 cm head required only 110 min to produce seepage whereas the second test required

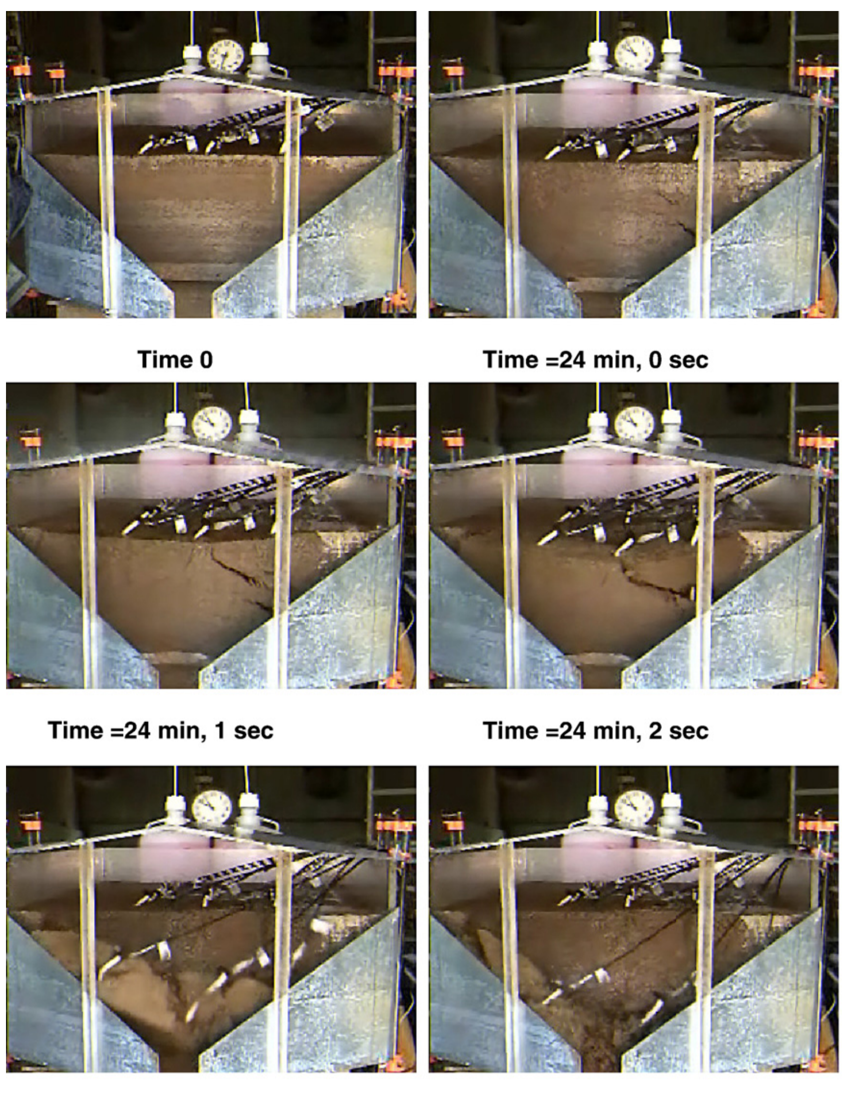

Fig. 5. Time sequence of first pop-out failure for rainfall with a 15 cm head on the soil-pipe.

954 min. At the time of seepage flow for the second run, only the tensiometers closest to the discontinuous pipe were close to saturation, Fig. 4A, and in fact tensiometers near the open face where seepage was occurring were exhibiting unsaturated conditions. This is evidence of the hydraulic non-equilibrium associated with preferential flow immediately above the water-restricting layer. Once rainfall started, tensiometers downslope from the pipe exhibit a dynamic response with those 5 cm above the open face exhibiting response 44 min after rainfall initiation and saturated conditions by 100 min after initiation.

Infiltration from the rainfall reduced the lateral hydraulic gradient resulting in much lower rates of flow through the discontinuous soil-pipe, Table 1. The average pipe flow rate for rainfall with a 15 cm head was 0.05 cm h^{-1} which is about a third of the flow rate into the pipe for pipe flow alone. The runoff rate for rainfall with pipe flow under a 15 cm head was 5.2 cm h^{-1} which was not different from rainfall alone. The average sediment concentration for the two 15 cm head with rainfall tests averaged over the three rainfall events, was 26.8 g L^{-1} which was somewhat higher than for rainfall alone. Sediment concentrations were more variable for the initial rainfall event for the first test with a peak of 99 g L^{-1} near the initiation of runoff with an average concentration for the three events of 32.0 g L^{-1}. For the second test, the initial rainfall event peaked at only 44 g L^{-1}, Fig. 4B, and averaged 21.7 g L^{-1} which was essentially the same as the rainfall alone. The total sediment loss by sheet erosion averaged 4.5 kg which is only slightly higher than for rainfall alone.

From the hydrometric measurements, i.e. soil–water pressures and runoff rate, and the sediment concentrations in the runoff it would appear that a 15 cm head on a discontinuous soil-pipe has a negligible influence on erosion. However, both 15 cm head with rainfall tests exhibited sudden mass failure that is commonly referred to as pop-out failures. For the initial 15 cm head test, the first pop-out failure occurred 24 min after rainfall started in which 2.3 kg of soil was loss by mass wasting in a 5 s span, Fig. 5. This was followed by three additional pop-out failures for a total of 30.8 kg of soil loss by mass wasting. For the second test, the first pop-out failure occurred 18 min after rainfall started with a total soil loss by mass wasting of 1.6 kg. Mass wasting by pop-out failures is consistent with the findings of Simon et al. (1999) for soils with contrasting permeabilities that result in rapid soil–water pressure increases. But it is in contrast to the cantilever type failures reported by Wilson et al. (2007) and Fox et al. (2006) where contrasting layers resulted in seepage erosion that undercut gully banks.

The 30 cm head with rainfall had even more dramatic mass wasting by pop-out failures. The data logger failed to record tensiometer values for the initial test of rainfall with a 30 cm head. However, the second test exhibited similar hydrologic behavior as for the rainfall with a 15 cm head. Antecedent conditions were around −45 cm, seepage began while tensiometers exhibited unsaturated conditions. Tensiometers did respond much quicker to rainfall for the 30 cm head with values sharply rising to positive pressures, Fig. 6B.

Runoff for the first 30 cm head with rainfall test began 15 min after rainfall initiation but only 3.5 min for the second test which

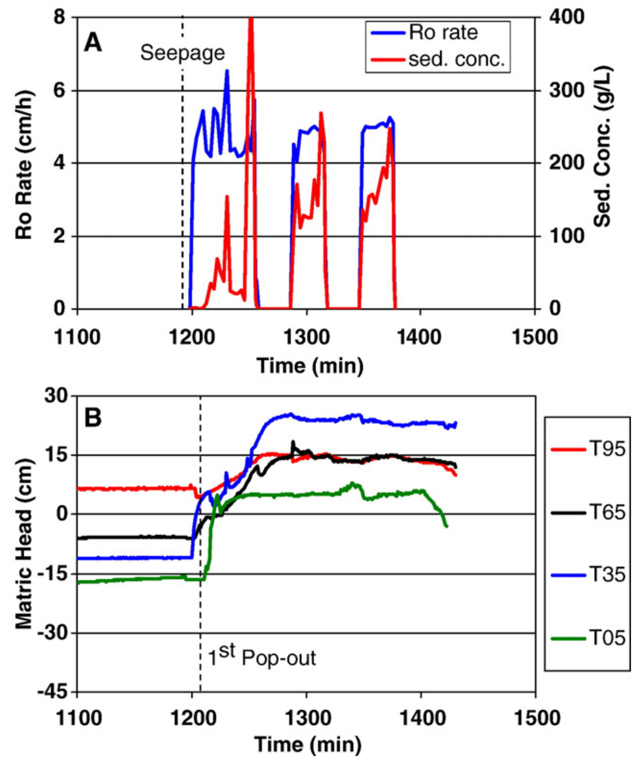

Fig. 6. (A) Runoff hydrograph and sedigraph response to the three rainfall events for the rainfall plus pipe flow with 30 cm head. (B) Tensiometer response to establishment of 30 cm head on the soil-pipe at positions T2 (95 cm), T5 (65 cm), T8 (35 cm), and T11 (5 cm) in Fig. 1. Dashed lines indicate time to seepage (A) and to first pop-out failure (B).

surprisingly averaged out to be slightly longer time to runoff compared to the rainfall alone and rainfall with 15 cm head. The runoff rates were essentially the same as the rainfall alone and rainfall with 15 cm head. While the hydrometric response was similar to the rainfall with a 15 cm head, the sediment concentrations in runoff for both tests of rainfall with a 30 cm head were much higher. The average sediment concentration over the three rainfall events was 49 and 122 g L^{-1} for the two tests respectively for a total soil loss by sheet erosion of 13.6 kg. Thus soil loss for rainfall with a 30 cm head, which is equivalent to a water table perched to the soil surface, was almost four times higher than for rainfall alone and three times higher than with a head of 15 cm on the soil-pipe. It is possible that the sediment concentrations, and therefore soil loss attributed to sheet erosion, for the rainfall with pipe flow may have been affected by the inability to collect all of the slumped material. However, given the care taken in sampling and the off-set by having sheet erosion material collected with the mass failure material, it is not likely to have resulted in the substantial differences in sheet erosion between the rainfall alone and rainfall with pipe flow.

However, the most dramatic impact of a 30 cm head on the soil-pipe was observed in the mass wasting. Mass wasting failures occurred within 17 min and 18 min after rainfall initiation for the two tests. The mass wasting from pipe flow again occurred as sudden, catastrophic pop-out failures. For the first test there were seven pop-out failures in the initial rainfall

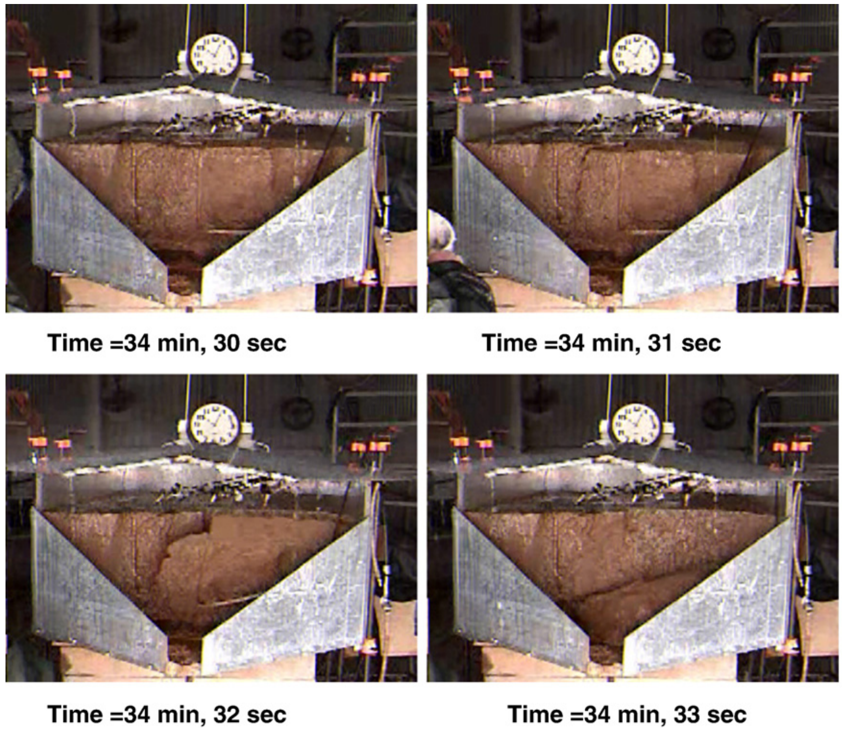

Fig. 7. Time sequence of tenth pop-out failure for rainfall with a 30 cm head on the soil-pipe.

event, each lasting a matter of seconds. The mass wasting for the individual pop-out failures ranged from 0.6 to 12.2 kg for a total of 37.4 kg. For the second test there were 16 pop-out failures for a total soil loss by mass wasting of 88.3 kg. The majority (13) occurred during the initial rainfall with two in the second rainfall and one in the last rainfall with a range from 0.6 to 15.4 kg loss by mass wasting. A typical pop-out is depicted in Fig. 7 which was pop-out number 10 which occurred 34.5 min after the start of the initial rainfall event. It lasted only 4 s and resulted in 3.1 kg of soil loss. The soil losses by mass wasting were generally four times greater than by sheet erosion for both the 15 and 30 cm heads, Table 1. Mass wasting for the 30 cm head with rainfall was more than an order of magnitude greater than sheet erosion for rainfall alone, Table 1.

3.4. Treatment differences

Significant differences (at the $P=0.05$ level) in hydrologic responses among treatments (rainfall alone, 15 cm head on pipe, 30 cm head on pipe, combinations), were determined using the SAS Proc GLM procedure (SAS, 1999), Table 1. Differences in timing of seepage and runoff initiation among treatments were not significant. Despite the fact that the 30 cm head exhibited 42% higher pipe flow rate for pipe flow alone treatment and almost 4 times greater flow rate for the pipe flow with rainfall treatments, the differences were not significant. This is due to the large variability in pipe flow rates and the lack of statistical power with only two replications.

The runoff rate for pipe flow alone treatments were the seepage rate expressed on an area basis. It is therefore not surprising that differences in runoff rate between the pipe flow alone and the treatments that included rainfall were significant. However, the combination of rainfall with pipe flow did not result in significantly higher runoff rate than rainfall alone. Despite the runoff rate and pipe flow rates not being significantly different, the sediment concentration, total soil loss by sheet erosion, and total soil loss by mass wasting was significantly higher for the combination of rainfall with pipe flow under a 30 cm head as compared to rainfall alone. The combination of rainfall with pipe flow under a 30 cm head also had significantly higher sediment concentration, sheet erosion, and mass wasting than the pipe flow alone. This further demonstrates the synergistic effect of pipe flow occurring during a rainfall event when the two processes are occurring simultaneously.

4. Conclusions

Preferential flow through macropores above a restrictive layer, e.g. fragipans, which are common in loess soils, can result in development of soil-pipes. Soil-pipes have been reported to cause ephemeral gullies, however, by definition these soil-pipes would be left discontinuous once the gully is filled-in by tillage operations. The impact of preferential flow through a discontinuous soil-pipe on erosion was quantified for two pressure heads (15 and 30 cm) on a 30 cm deep soil bed through a series of tests with and without rainfall.

Rainfall alone on bare, freshly tilled soil resulted in rapid runoff with high soil losses by sheet erosion equivalent to 25 T ha^{-1}. However, rainfall alone did not result in ephemeral gully development or head-cut migration. These findings supported the concept that preferential flow can cause hydraulic non-equilibrium conditions in which seepage occurs while tensiometers near the flow path indicate unsaturated conditions. Seepage due to flow through a soil-pipe may continue for long periods after a rainfall event. In the case of seepage through soil-pipe continuing after the land has been tilled and the soil-pipe buried and made discontinuous, such flow was found to result in negligible soil loss in three of the four tests.

The main difference between rainfall or pipe flow alone and rainfall with pipe flow occurring simultaneously is in the mass wasting. When pipe flow occurs with rainfall, such as a typical rainfall event in which a perched water table is established on a pre-existing buried soil-pipe, a synergistic effect is produced that not only results in nearly four times higher sheet erosion but causes sudden and cataclysmic pop-out failures which may be up to 20 times higher than sheet erosion. The result of these pop-out failures is the re-establishment of ephemeral gullies with large initial soil losses. This finding explains the reoccurrence of ephemeral gullies in the same locations despite land management efforts to control their development. This work also suggest that conservation practices that focus on controlling the surface runoff may be ineffective if subsurface flow controls are not considered. Locations susceptible to subsurface flow may benefit more from drainage and/or deep rooted vegetation control practices.

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